Dynamic Force Reconstruction of Transient Flap Control Force Experiments in a Hypersonic Wind Tunnel

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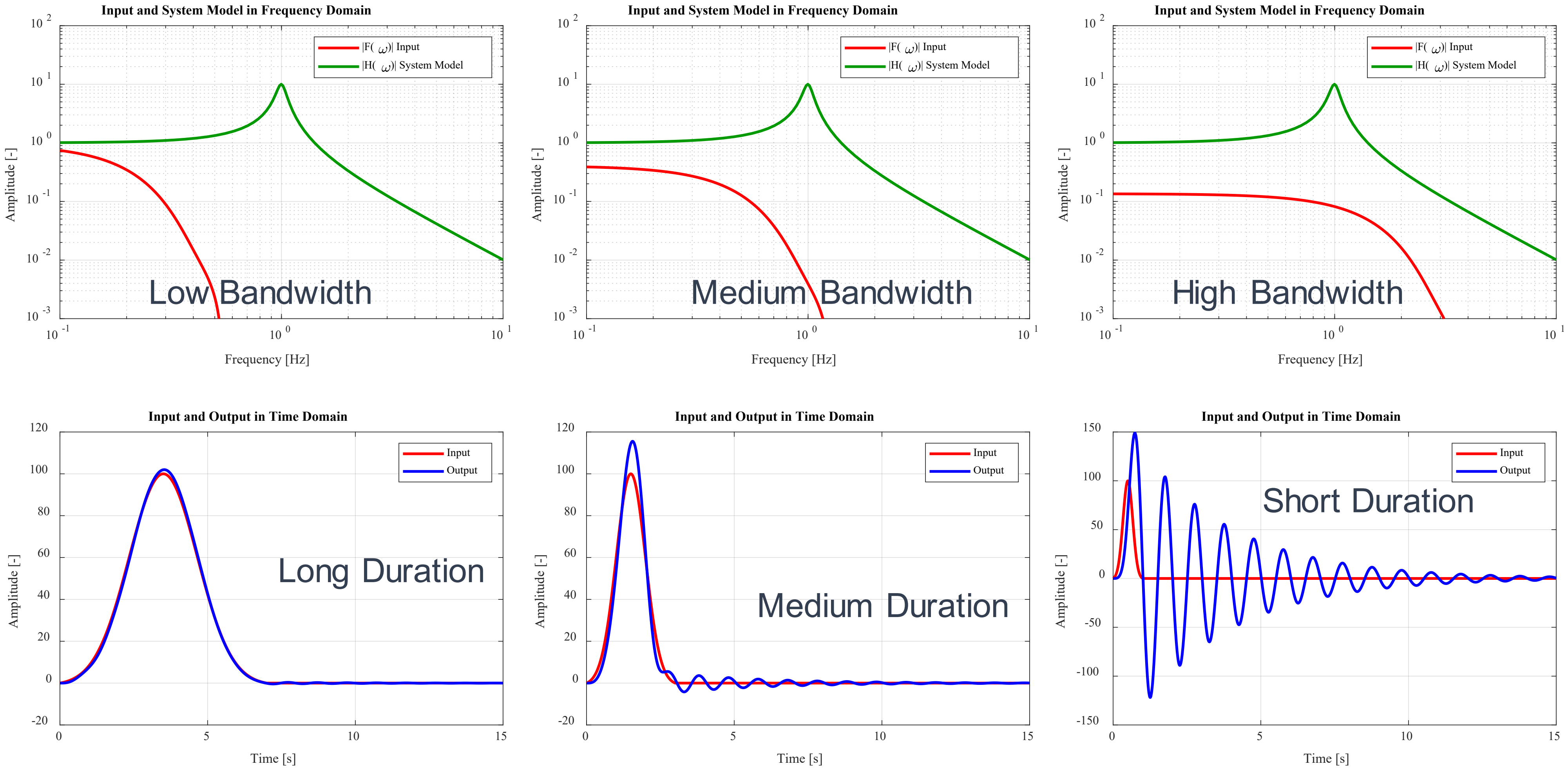
Dynamic Force Reconstruction Background

- Transient and high frequency forces and moments are NOT measurable using current measurement technology
- Aerodynamic and structural loads are coupled
- Wind tunnel measurement applications
  - Shock tunnel force and moment (F&M) measurements
  - Scramjet engine unstart
  - Divert thruster firing
  - Shroud separation
  - Store separation
  - Transient jet interaction

Effect of High Input Bandwidth

As the input bandwidth is increased (and duration is decreased), the system character starts to show up in the system output



Quasi-Static Measurement is Valid Here

Dynamic Force Reconstruction is Recommended Here

Dynamic Force Reconstruction is Needed Here

Test Objectives

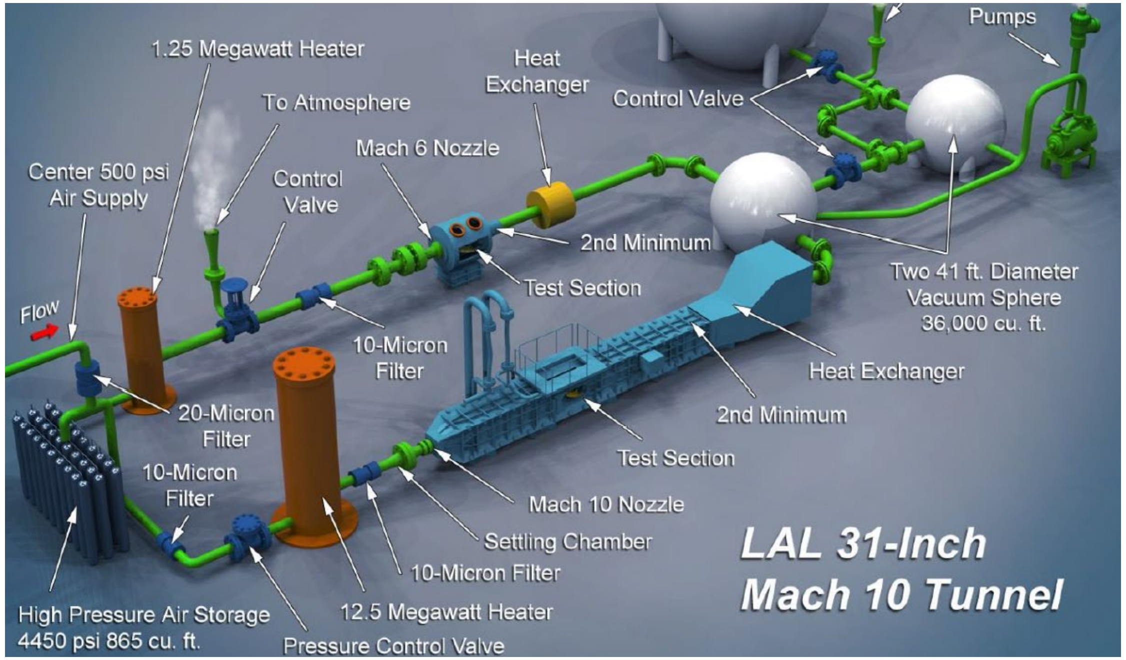
1. Collect high bandwidth force and acceleration data during a hypersonic wind tunnel test

2. Demonstrate dynamic force and moment measurement methodology

3. Compare dynamic force and moment measurement to conventional quasi-steady force measurement

Wind Tunnel Overview

- Tunnel runs conducted in NASA Langley Research Center's (LaRC) Mach 10 facility in March of 2023
- Facility has long run times (>60 sec) and a side viewing port – both ideal for the transient loads of this test

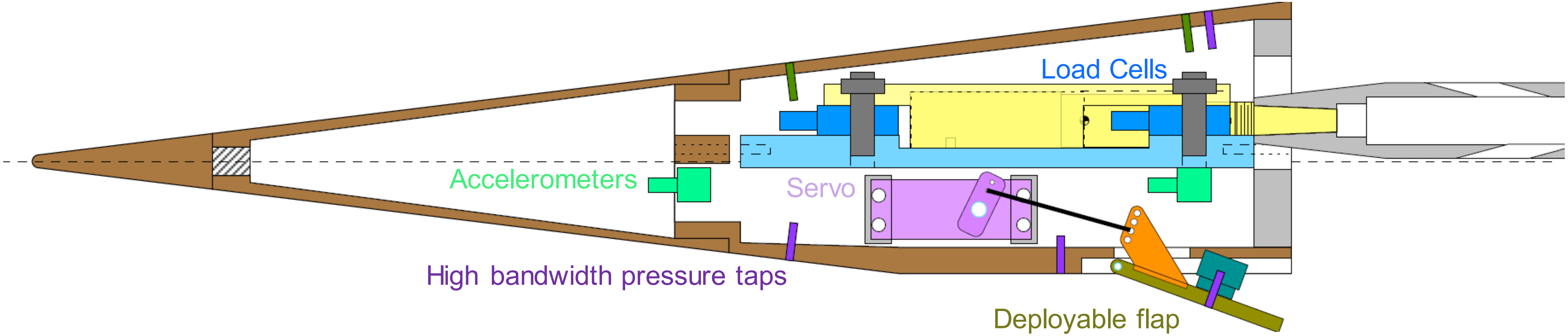


Variable	Unit	Condition 1	Condition 2	Condition 3	Condition 4
P_{t1}	(psi)	350	720	1300	1450
T_{t1}	(°R)	1775	1790	1790	1790
P_∞	(10^{-2} psi)	1	1.89	3.19	3.52
T_∞	(°R)	93.68	92.23	90.35	90.26
q_∞	(psi)	0.66	1.27	2.2	2.43
U_∞	(ft/s)	4593.4	4614.6	4618.3	4626.1
M_∞	-	9.68	9.81	9.93	9.96
Re_∞	(10^6/ft)	0.53	1.04	1.82	2.03
Re_2	(10^6/ft)	0.49	0.93	1.61	1.78
ρ_2/ρ_∞	-	5.96	5.97	5.97	5.98
P_{t2}	(psi)	1.22	2.36	4.07	4.51

Reference: K. T. Berger, K. E. Hollingsworth, S. A. Wright, and S. J. Rufer, "NASA Langley Aerothermodynamics Laboratory: Hypersonic Testing Capabilities," in *53rd AIAA Aerospace Sciences Meeting*, Kissimmee, Florida: American Institute of Aeronautics and Astronautics, Jan. 2015. doi: 10.2514/6.2015-1337.

Test Article Overview

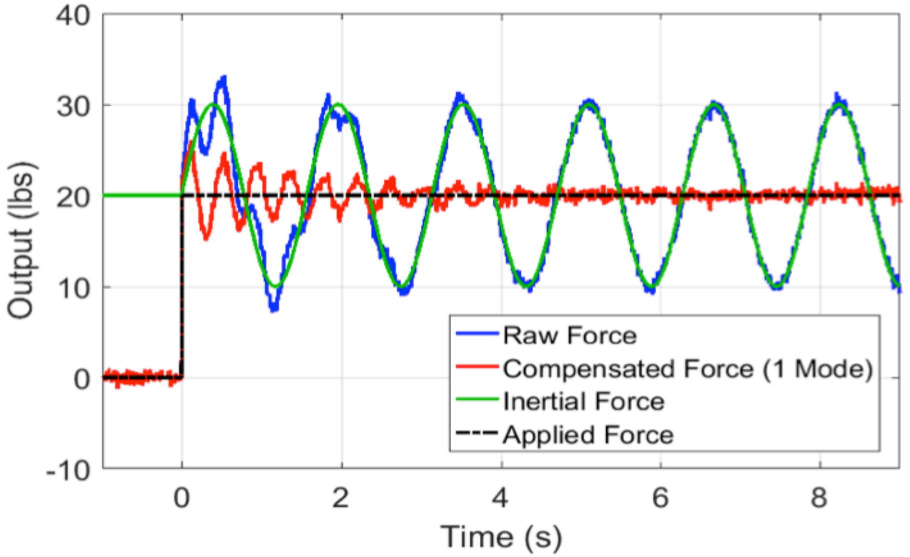
- Test article is a 7° half angle titanium cone with an aft slice
- Aft slice embeds a fast acting servo capable of actuating at 1°/ms
- Fast (~40 ms) triangle pulse is applied dynamic load – currently unmeasurable with standard wind tunnel measurement technology
- Custom dynamic force balance mounted within model
  - High bandwidth, piezoelectric load cells and accelerometers
  - Standard, strain gage roll balance



Methodology Overview

SWAT

- The Sum of Weighted Accelerations Technique (SWAT) is arguably the most commonly used method in the wind tunnel community
- SWAT follows a natural approach where the inertial contribution (green) of the force is combined with the elastic contribution (blue) to get the applied external force (red)
- The method presented by Draper et al. is a slight modification of the typical approach where each modal frequency is scaled separately



$$\boxed{F_{rec}} = \boxed{S_S C_S} + \boxed{\sum_{l=1}^{l=L} S_{A,l} C_{A,l}}$$

Reference: J. W. Draper, S. Lee, and E. C. Marineau, "Development and Implementation of a Hybrid Dynamic Force Measurement System at AEDC Tunnel 9," American Institute of Aeronautics and Astronautics, Jan. 2017. doi: 10.2514/6.2017-1593.

Methodology Overview

TDDM

- The Time Domain Deconvolution Method (TDDM) formulates the problem via the convolution method
  - Individual input-output (e.g., point force-acceleration channel) pairs are related via an impulse response function (IRF)
  - IRFs are combined via an impulse response matrix (IRM)
  - System must be linear and time-invariant (LTI)
- In this work, we use the formulation presented by Draper et al. which introduces a constraint parameter *R* which when increased, improves the conditioning of the IRM prior to matrix inversion
  - IRM determined empirically via modal testing
  - Applied output (u) solved by inverting IRM (B) and premultiplying by measured outputs (y)
  - Derivation provided by Draper et al. 2018

$$y(t) = \int_0^t h(t-\tau)u(\tau)\mathrm{d}\tau = h * u(t) \Longrightarrow y(t_k) = \sum_{i=0}^{N}\left[\sum_{j=0}^{M}\left[h_{k-i\cdot R_2-j} \quad h_{k-i\cdot R_2-j-1}\right]\int_{s_h=0}^{s_h=1}\mathbf{N}_h\hat{\mathbf{N}}_u \mathrm{d}s_h\right]\mathbf{u}_{i+1}\Delta t_s \Longrightarrow \mathbf{y} = \hat{\mathbf{B}}\mathbf{u}\Delta t_s$$

Reference: J. W. Draper III and S. W. Lee, "Smooth construction of impulse response functions and applied loads using a time domain deconvolution method," *Journal of Sound and Vibration*, vol. 443, pp. 430–443, Mar. 2019, doi: 10.1016/j.jsv.2018.11.050.

Methodology Overview

FDIM

- The Frequency Domain Inverse Method (FDIM) is a frequency domain couple to TDDM
- For computational efficiency, the convolution formulation is transformed to the frequency domain via a Fourier transform
  - Each frequency of an input and output are related via a scalar
  - One may solve for the applied input at each frequency and invert via an inverse Fourier transform to obtain the time domain applied force
- In this work, we use the formulation presented by Draper which allows for multiple calibration input repetitions to better converge the IRM

$$y(t) = \int_0^t h(t-\tau)u(\tau)\mathrm{d}\tau = h * u(t)$$

Fourier Transform

$$Y(\omega) = H(\omega)U(\omega)$$

Multiple Input and Outputs

Frequency contribution of *p* input locations

$$\begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_p \end{pmatrix}_\omega = \begin{pmatrix} U_1 \\ U_2 \\ \vdots \\ U_p \end{pmatrix}_\omega H(\omega)$$

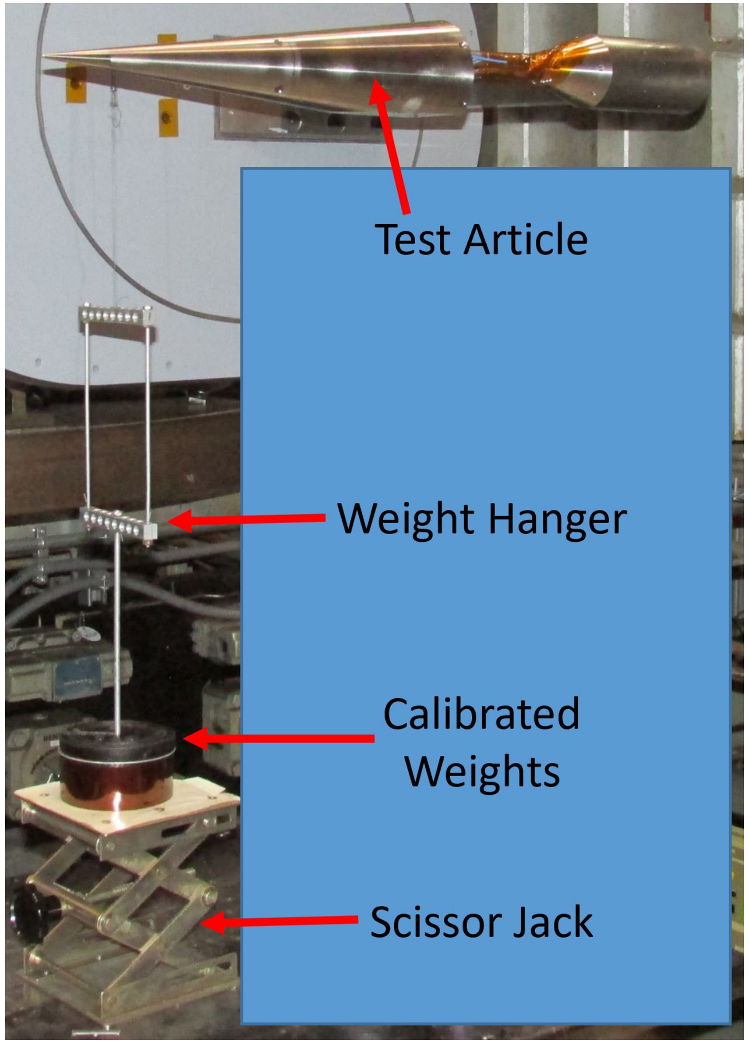
Frequency contribution of *p* output channels

Frequency contribution of system IRM

Reference: Draper III, John Willis, "Dynamic Force Measurement in Hypersonic Wind Tunnels," Dissertation, University of Maryland, College Park, 2019. [Online]. Available: https://drum.lib.umd.edu/handle/1903/25119

Calibration Overview
SWAT

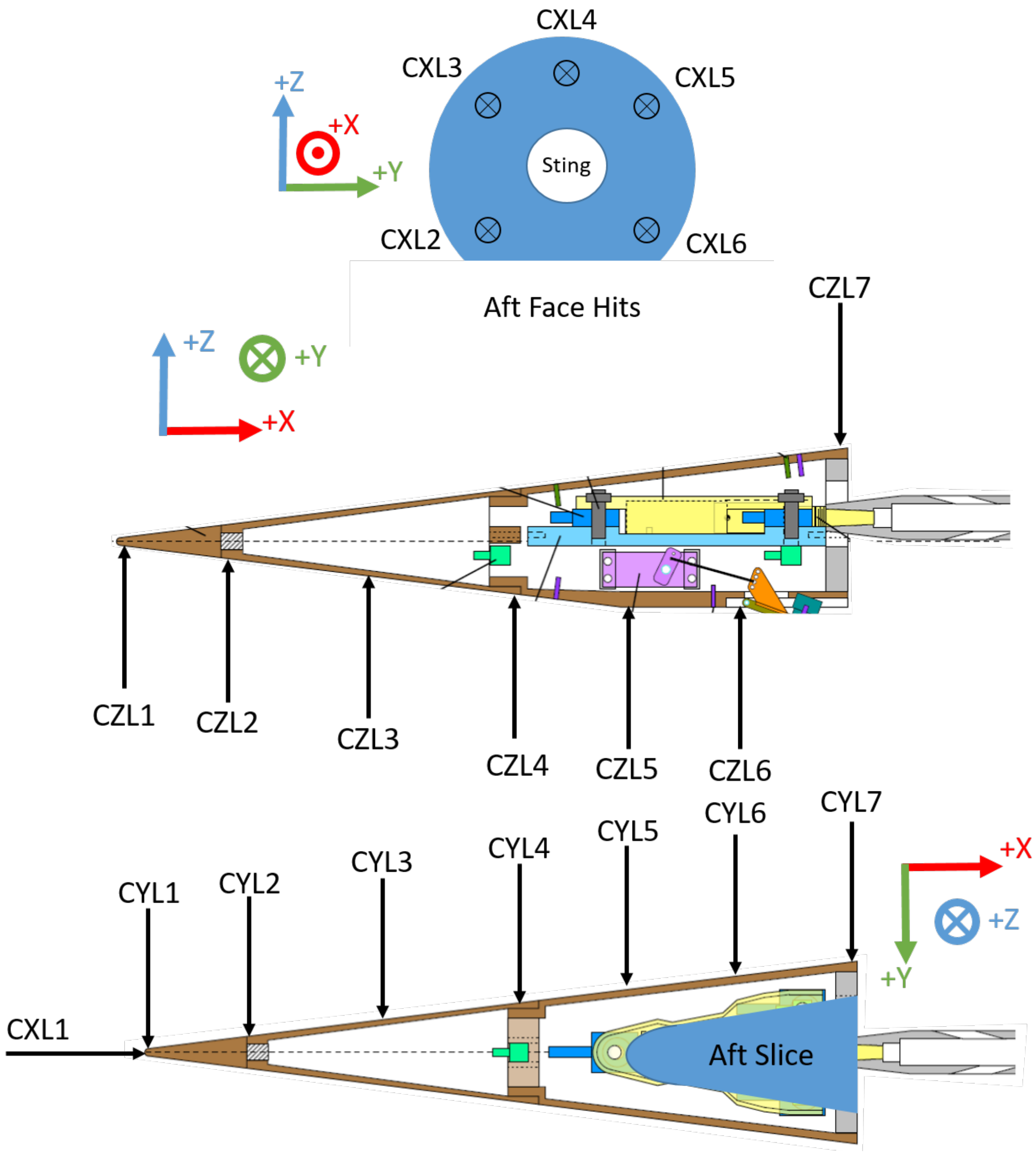
- To calibrate the SWAT static and dynamic calibration matrices, the authors utilized a weight hanging method at various locations over the test article
  - Static calibrations – apply loads smoothly and record peak voltages
  - Dynamic calibrations – sever string holding weight to record acceleration scaling voltages
- Due to test setup limitations, only normal, axial, pitch, and roll were calibrated
- Side and yaw directions could be conducted in the future with a pulley system but were deemed less important for this demonstration



Calibration Overview

TDDM and FDIM

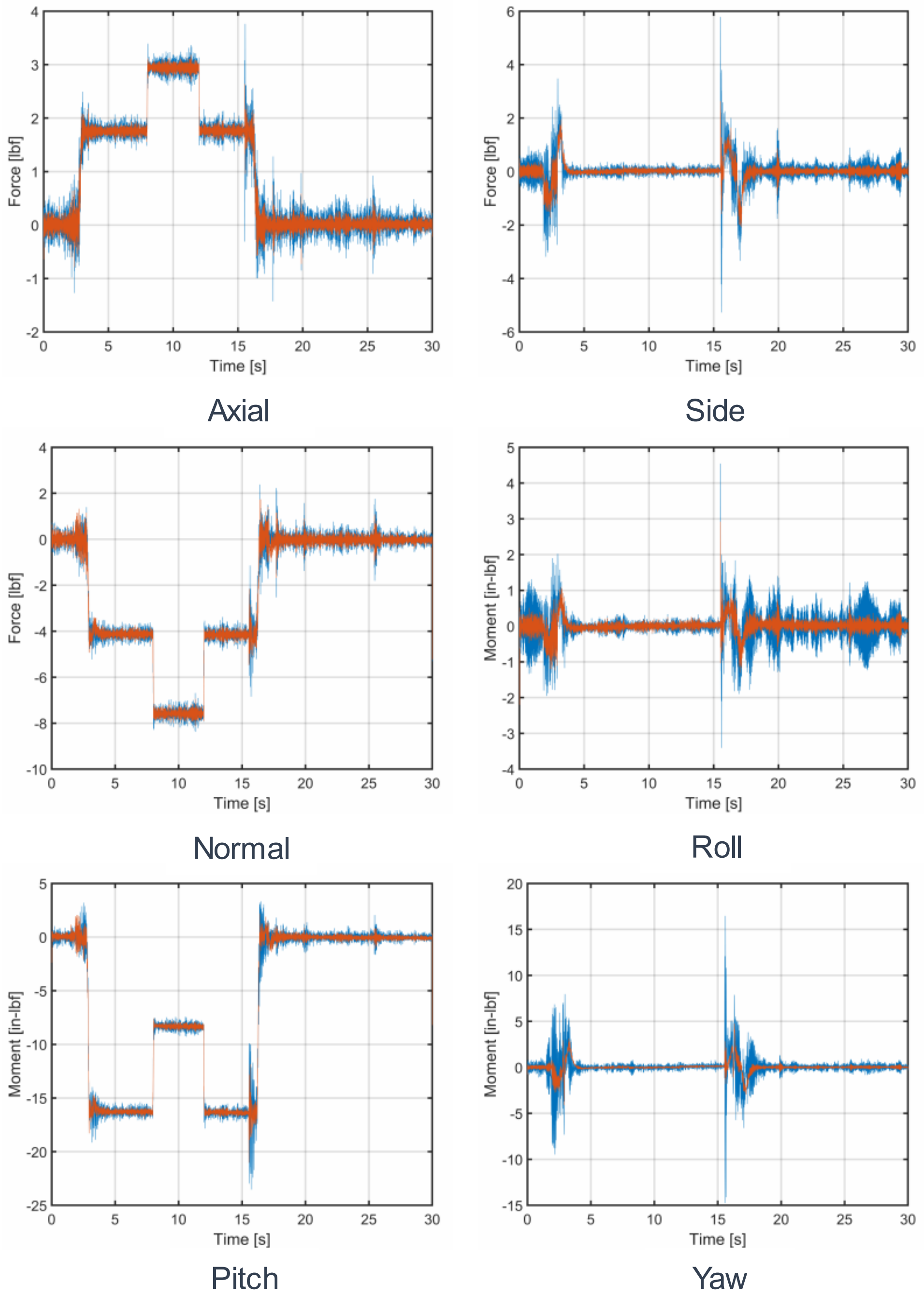
- Since TDDM and FDIM relate input and output pairs, an instrumented impulse hammer is used to record the IRFs for each pair
- Calibrations were conducted in each of the three cardinal directions and at various locations
- A minimum of ten taps at each locations were performed
- The calibration from the softest tip hammer was used to ensure most of the input energy was focused on the dynamics of interest (<500 Hz)



Current Results

SWAT

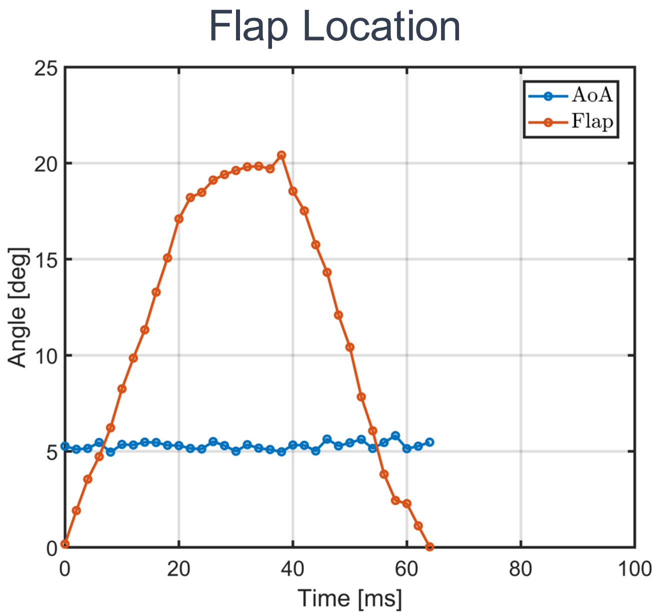
- SWAT was applied to run 34 – a single five second ramp and hold test (T=7 to 12 sec)
- It is evident that the ramp does not significantly excite dynamics during the tunnel operation
- Therefore, reduction of modal dynamics via SWAT is correspondingly minimal
- Interestingly, during insertion (T=2 sec) and ejection (T=15 sec) of the test article from the tunnel, large loads are applied (relative to ambient tunnel noise) and the SWAT has more success at reducing the ambient tunnel noise

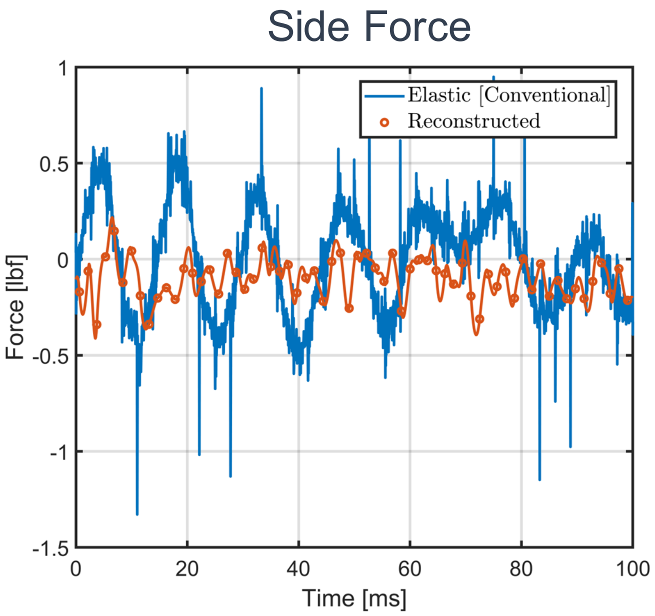


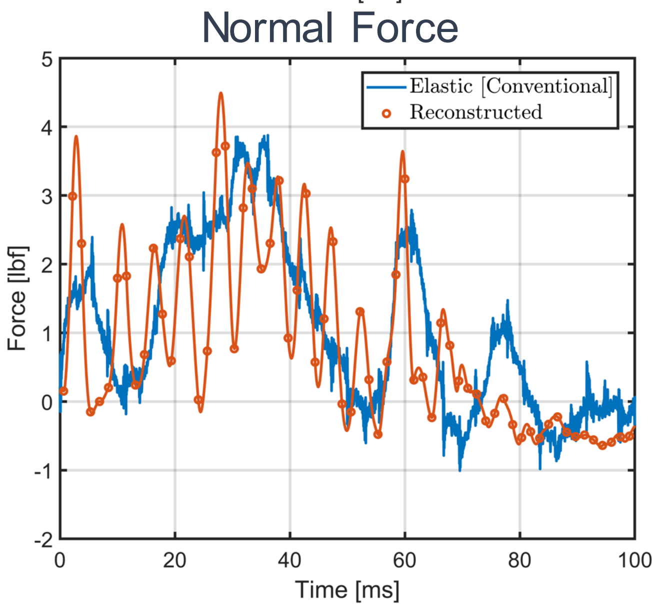
Current Results

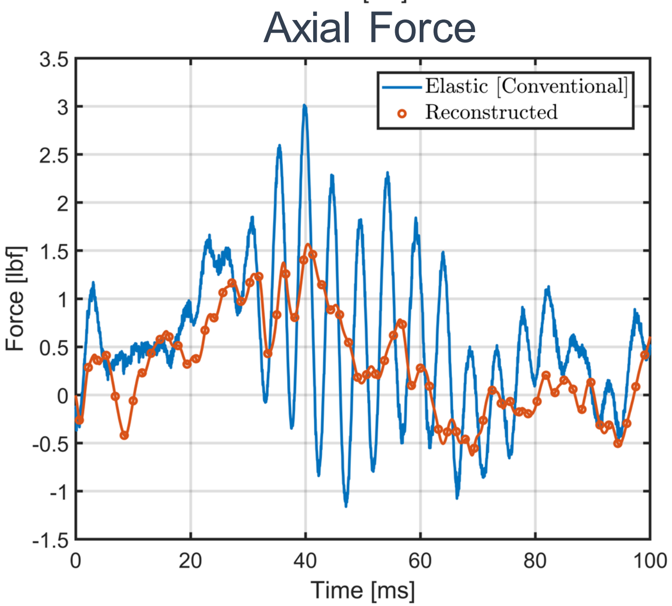
TDDM

- TDDM was applied to run 33 – a single flap pulse to 20 degrees as
- Pulses were reconstructed at calibration locations CXL1, CYL7, and CZL6
- Observations
  - Side force oscillations reduced
  - Axial force oscillations reduced
  - Normal force appears to have three pulses (at flap open, full extension, and close)
  - Normal force appears to have substantial residual oscillations





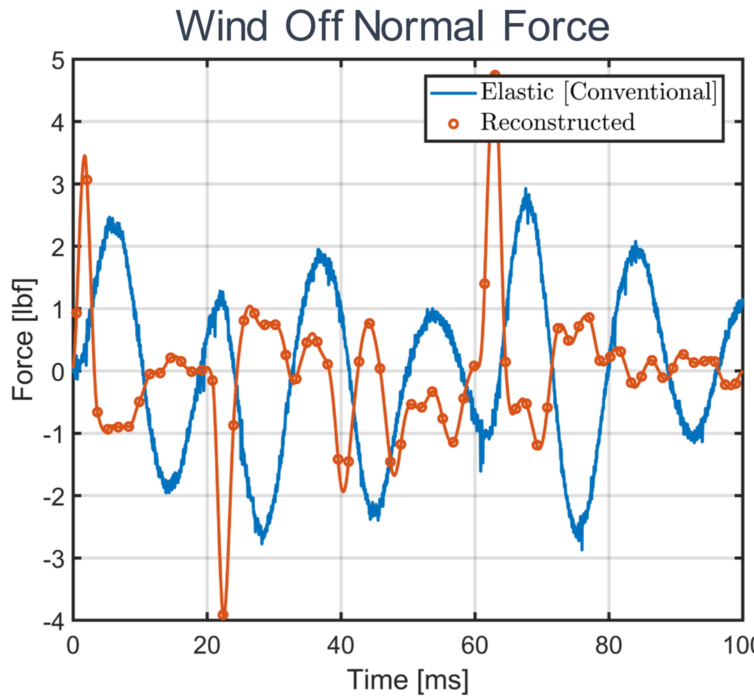


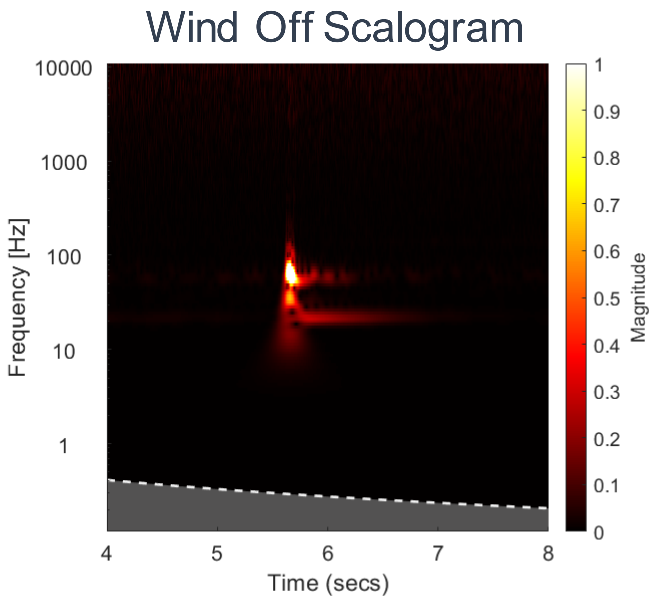


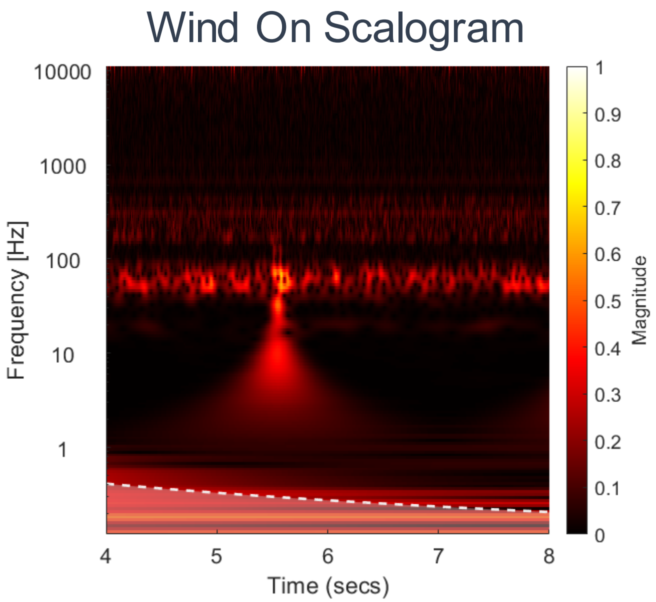
Current Results

TDDM – Wind Off

- To further explore these unexpected pulses, a similar, wind-off run was conducted to remove the variable of flow
- Applying TDDM to this wind off pulse deflection revealed that internally applied forces are evident due to flap actuation
- Additionally, the ambient tunnel noise appears to be on the order of the applied load (See scalograms)
- This is discussed further in the paper but the relatively low signal to noise ratio is a further challenge to reconstruction accuracy



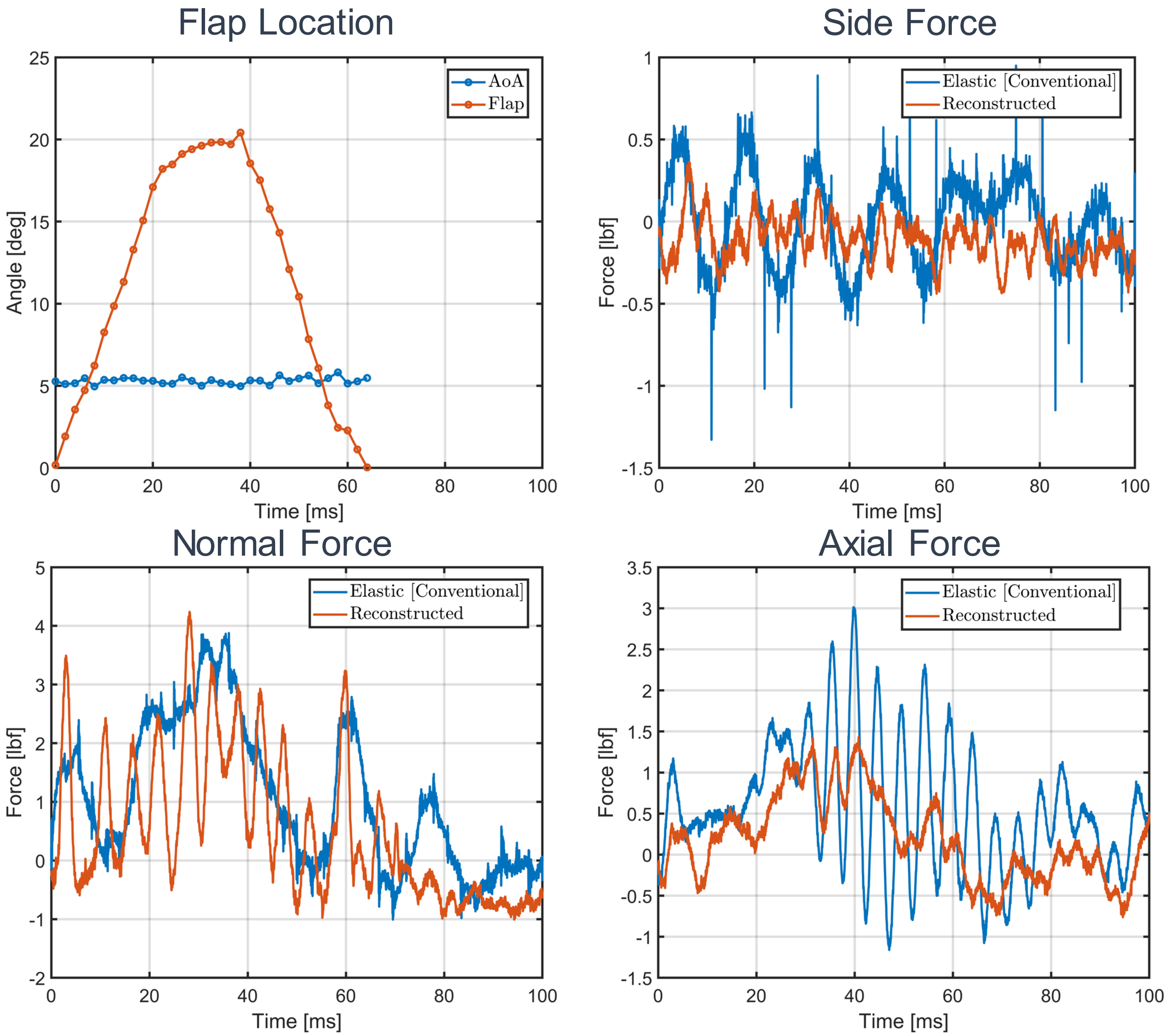




Current Results

FDIM

- The FDIM results are qualitatively similar to those of the TDDM
- This is expected as they're of similar formulation and using the same input-output data for calibration and test (run 33)
- The conclusions stated in regards to the TDDM hold for this method



Conclusions

- Next generation hypersonic vehicles are likely to lean on technology that is difficult to test in wind tunnels currently – gas jets, inlet effects, and rapidly deployed control surfaces are being increasingly utilized in vehicles and the effectiveness of these cannot be measured using current force and moment measurement technologies
- Dynamic force reconstruction technology is necessary for high bandwidth input measurement
- JHU/APL, NASA LaRC, UMD, and AEDC Tunnel 9 conducted a joint hypersonic wind tunnel test to obtain a rich dataset for future dynamic force reconstruction study
- In this paper, the authors summarize the test and provide initial results for three methods familiar to them
- Initial results raise new questions, but the authors hope that this work and data can continue to be used to advance the field of dynamic force reconstruction

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